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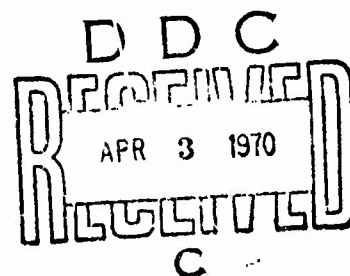
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AIR FORCE SURVEYS IN GEOPHYSICS, NO. 212



**AIR FORCE CAMBRIDGE RESEARCH LABORATORIES**  
L. G. HANSCOM FIELD, BEDFORD, MASSACHUSETTS

# **PRECIPITATION AND CLOUDS: A Revision of Chapter 5, Handbook of Geophysics and Space Environments**

A.E. COLE  
R.J. DONALDSON  
R. DYER  
A.J. KANTOR  
R.A. SKRIVANEK



**OFFICE OF AEROSPACE RESEARCH**  
United States Air Force



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ENVIRONMENTAL CONSULTATION SERVICE

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## **Abstract**

The need for geophysical and astrophysical information is critical for the design of aircraft, missiles, and satellites. The HANDBOOK OF GEOPHYSICS AND SPACE ENVIRONMENTS is an attempt by the U.S. Air Force to organize some of these data into compact form.

The water content of the atmosphere is discussed in this chapter. Data are provided on the frequency of occurrence of various surface rates of rainfall, hail, the vertical distribution of precipitation intensity, and the particle size distribution in widespread precipitation. Information on the types and limitations of cloud data and of the distribution and water content of clouds is included.

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## Preface

This report is a revision of Chapter 5 of the Handbook of Geophysics and Space Environments\*. (Numbers of Sections are the same as those in the original Handbook so that the cross-referencing system in other chapters remains valid). This survey represents the state of the art in August, 1969 when the manuscript was submitted.

Most of the available meteorological measurements were, until recently, made in English units, and conversion of some of these data to the metric system would convey a false impression of the precision of the measurements. As a result, this chapter contains a mixture of metric and English units; wherever practical, the metric value is inserted after the English.

SHEA L. VALLEY

Scientific Editor

Handbook of Geophysics and Space Environments

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\* Published by the Air Force Cambridge Research Laboratories and by the McGraw-Hill Book Co. in 1965.

## **PRECIPITATION AND CLOUDS: A Revision of Chapter 5, Handbook of Geophysics and Space Environments**

### **5.1 PRECIPITATION by A.E. Cole and R.J. Donaldson**

The frequency of occurrence of given rates of precipitation and the associated vertical distributions of various precipitation parameters must be considered when designing equipment and weapons systems. For example, in designing a search radar, one must know the frequency of occurrence of the critical rainfall rate over the proposed regions of operation in order to determine the probability of failure due to attenuation by rainfall.

In designing jet engines, one must know the amount of water and ice likely to be ingested at various altitudes. Hail (and associated large raindrops) encountered by an aircraft or missile at high speeds can cause damage. Solving design problems, such as aircraft and radome erosion by precipitation, requires a knowledge of the variation of the rainfall rate and raindrop size distributions with altitude. Such data must be related to surface rates of rainfall so that the probability of occurrence for specific areas can be determined from available data. This section gives examples of the types of precipitation information available.

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(Received for publication 5 November 1969)

### 5.1.1 Surface Rates of Precipitation

Usually, tabulations of occurrences of various rates of precipitation cannot be obtained directly from existing climatological records. Precipitation data for most areas of the world are limited mainly to average monthly, seasonal, and annual totals, and to the number of days on which precipitation fell. Clock hourly (totals on the hour every hour) precipitation data are available for numerous stations in the United States and Europe, but for only a few stations elsewhere. Frequencies of occurrence of instantaneous rates of precipitation have been computed for a small number of stations in the United States.

Given below are methods for obtaining the frequencies of occurrence of specific clock hourly and instantaneous rates of precipitation at stations where only the total annual amount of precipitation and number of days on which precipitation occurred are known.

#### 5.1.1.1 CLOCK HOURLY RATES

Figures 5-1, 5-2, and 5-3 were prepared by plotting against an index the frequencies of occurrence of clock hourly precipitation rates determined from climatic data for 22 stations in the United States and Europe. This index is the average per day of measurable precipitation, obtained by dividing the total annual precipitation by the number of days with measurable precipitation of 0.01 or more inches (0.25 mm or more). The standard error of estimates ( $S_y$ ) and the correlation coefficients ( $\gamma$ ) given for the regression equations (Y) in each figure indicate that a good linear relationship exists between these parameters. Assuming this relationship is valid for other warm temperature to subpolar areas, approximate annual frequency of occurrence of clock hourly precipitation rates at other stations in the temperature zone can be determined from the regression curves shown when only the average annual total precipitation and the number of days with 0.01 or more inches are known. Because data from all North American and European areas used in these correlations fit equally well on the derived curves in Figures 5-1, 5-2 and 5-3, this assumption appears valid. The standard error of estimate indicates that data obtained from these curves will be within 30, 10, and 8 h yr<sup>-1</sup> 68% of the time for rates  $\geq 0.06$ , 0.12, and 0.18 inch h<sup>-1</sup> (1.5, 3.0, and 4.6 mm h<sup>-1</sup>) respectively.

Table 5-1 gives approximate frequencies of occurrence of clock hourly precipitation rates, obtained from Figures 5-1, 5-2, and 5-3, for a few stations.

#### 5.1.1.2 INSTANTANEOUS RATES OF PRECIPITATION

Instantaneous rates of rainfall may vary considerably within one hour. For example, 0.06 inch precipitation may be reported during a clock hour. It could have accumulated in thirty minutes at a rate of 0.12 inch h<sup>-1</sup>, in twenty minutes

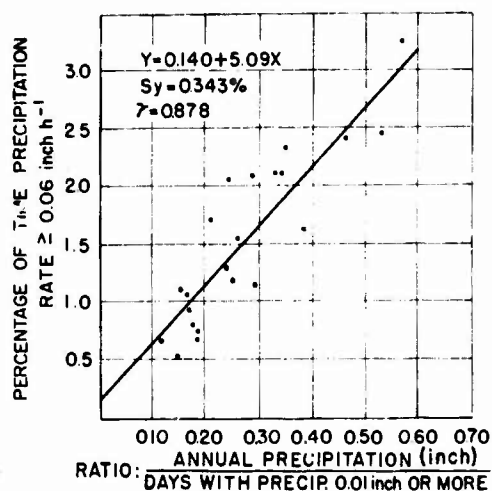


Figure 5-1. Correlation Between Annual Probability of Clock Hourly Precipitation Equal to or Exceeding  $0.06 \text{ inch } h^{-1}$  and Usually Available Precipitation Data

Figure 5-2. Correlation Between Annual Probability of Clock Hourly Precipitation Equal to or Exceeding  $0.12 \text{ inch } h^{-1}$  and Usually Available Precipitation Data

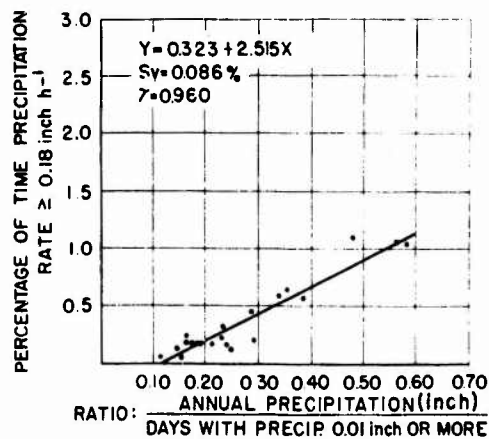
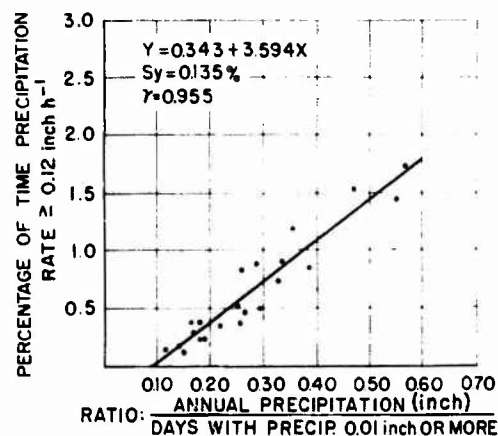


Figure 5-3. Correlation Between Annual Probability of Clock Hourly Precipitation Equal to or Exceeding  $0.18 \text{ inch } h^{-1}$  and Usually Available Precipitation Data

Table 5-1. Percentage of Time During an Average Year in Which Clock Hourly and Instantaneous Rates of Precipitation Equal or Exceed 0.06, 0.12, and 0.18 inch  $\text{h}^{-1}$  (1.5, 3.0, and 4.6 mm  $\text{h}^{-1}$ , at selected stations)

Station		Average Annual Precip. (inch)	Number of Days with Measurable Precip.	Clock Hourly Rates			Instantaneous Rates		
				0.06 (%)	0.12 (%)	0.18 (%)	0.06 (%)	0.12 (%)	0.18 (%)
Athens	37° 30' N 23° 43' E	15.70	98	0.94	0.24	0.08	0.85	0.23	0.08
Berlin	52° 30' N 13° 25' E	22.88	169	0.84	0.16	0.03	0.76	0.15	0.03
Dublin	53° 20' N 6° 15' W	27.37	218	0.78	0.13	0.01	0.70	0.12	0.01
London	51° 25' N 0° 20' E	24.47	167	0.89	0.20	0.06	0.80	0.19	0.06
Moscow	55° 45' N 37° 37' E	24.13	132	1.05	0.30	0.13	0.95	0.29	0.13
Paris	48° 52' N 2° 20' E	22.62	160	0.84	0.16	0.03	0.76	0.15	0.03
Rome	41° 45' N 12° 15' E	26.70	105	1.45	0.59	0.33	1.31	0.55	0.03
Tokyo	35° 41' N 139° 46' E	61.40	149	2.22	1.13	0.72	2.00	1.06	0.72
Warsaw	50° 14' N 21° 00' E	22.21	164	0.84	0.16	0.03	0.76	0.15	0.03
Washington	38° 55' N 77° 00' W	42.20	124	2.11	0.90	0.60	1.90	0.85	0.60

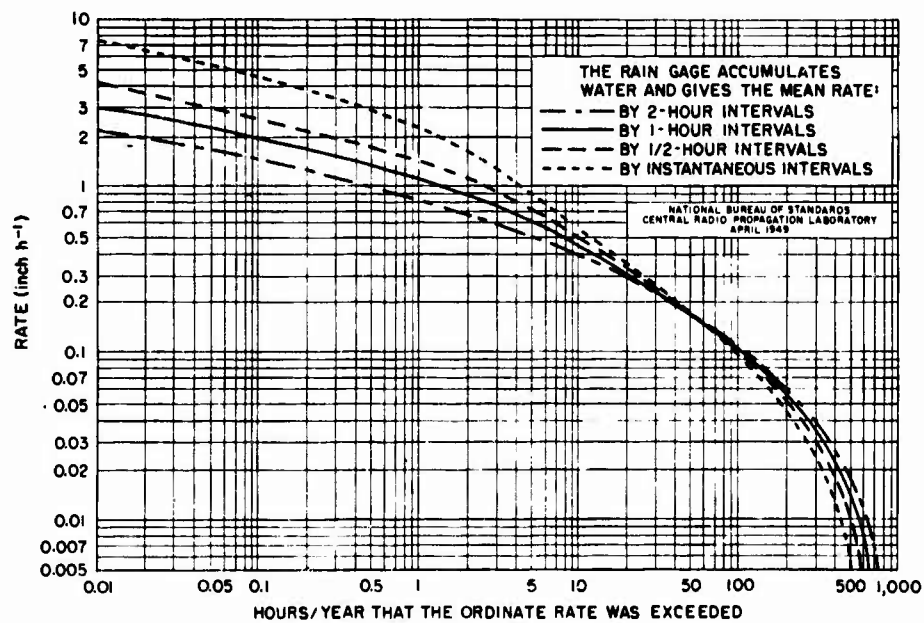


Figure 5-4. Cumulative Distribution of Rainfall Rates at One Location, Washington, D.C. The 1-hour curve is based upon observed long-time data; the other three curves are derived from the 1-hour curve. (From H. E. Bussey, 1950)

at the rate of  $0.18 \text{ inch h}^{-1}$ , or linearly over the entire hour. Thus, the length of time to be tabulated for computing the frequency of various rates cannot be determined directly from hourly data.

Distribution curves from instantaneous (one-minute periods) and hourly observations for the same station show how the instantaneous rate distributes itself around the clock hourly rate. These instantaneous curves may be used to break down the long-term clock hourly rates into shorter instantaneous segments, and the segments then compounded into a cumulative yearly distribution curve. Figure 5-4 shows cumulative curves and similar curves for 2-hourly and 1/2-hourly precipitation rates. A comparison of the frequency curves indicates that it makes little difference in the annual frequency for rainfall rates between  $0.06$  and  $0.18 \text{ inch h}^{-1}$  whether these rates are based on 2 h, one h, 1/2 h, or instantaneous time increments. The annual frequency of the instantaneous rate is approximately 90% of the mean hourly rate of  $0.06 \text{ inch h}^{-1}$ , 94% for  $0.12 \text{ inch h}^{-1}$ , and 100% for  $0.18 \text{ inch h}^{-1}$ . Because the Washington, D.C. area receives all precipitation types, and because there is nearly a one-to-one relationship for the three rainfall rates, it is considered reliable to adjust hourly frequencies to instantaneous frequencies in other areas on the basis of this analysis. The clock hourly frequencies for stations in Table 5-1 were converted to instantaneous frequencies by using the relationship described above.

Table 5-2 gives the probability of occurrence of given instantaneous rates (hourly rate for one min) of precipitation up to and exceeding  $7.50 \text{ inch h}^{-1}$  for New Orleans. New Orleans was selected because it is a representative station in an area of heavy rainfall and one for which the frequencies of clock hourly rates, based on 30 years of records, are available. The clock hourly rates were converted to instantaneous frequencies by using the relationship Bussey (1950) found to exist between the two rates in his analysis of rainfall rates at Washington, D.C.

Table 5-3 contains the approximate frequency with which given instantaneous rates of precipitation up to  $1.50 \text{ inch h}^{-1}$  are equalled or exceeded at stations in four climatic areas of the United States. Data for Portland and Washington are representative of conditions found on the northwestern and mideastern coasts, respectively. New Orleans represents an area of heavy rainfall frequency under the influence of tropical maritime air, and Oklahoma City represents the Great Plains.

#### 5.1.1.3 SEPARATION OF RAINFALL AND SNOWFALL

The data considered thus far are for precipitation as a whole, mainly snow and rain. To obtain the frequencies of rates of rainfall, the rates of snowfall  $\geq 0.06$ ,  $0.12$ , and  $0.18 \text{ inch h}^{-1}$  ( $1.5$ ,  $3.0$ , and  $4.6 \text{ mm h}^{-1}$ ) must be subtracted from the data in Table 5-1. A detailed examination of the clock hourly rates of

Table 5-2. Frequencies With Which Instantaneous Rates of Precipitation Equal or Exceed the Indicated Rates in New Orleans. (After R. D. Fletcher, Trans. Am. Geophys. Union, v. 31, p. 344, 1950)

Instantaneous Rate*		Frequency		
(inch h <sup>-1</sup> )	(cm h <sup>-1</sup> )	%	(h yr <sup>-1</sup> )	Occurrence Probability
0.06	(0.15)	2.16	189	1 in 46
0.18	(0.46)	1.08	95	1 in 92
0.40	(1.02)	0.56	49	1 in 179
0.80	(2.03)	0.37	32	1 in 274
1.50	(3.81)	0.21	18	1 in 487
3.00	(7.62)	0.044	3.85	1 in 2275
7.50	(19.05)	0.0011	0.096	1 in 91,250

\* Hourly rate for one minute.

Table 5-3. Approximate Percentages of Time During an Average Year When Given Instantaneous Rates of Precipitation are Equalled or Exceeded at Four Stations in the United States

Precipitation Rate (inch h <sup>-1</sup> ) (cm h <sup>-1</sup> )	.04 (.10)	.06 (.15)	.08 (.20)	.12 (.30)	.18 (.46)	.20 (.51)	.40 (1.02)	.80 (2.03)	1.50 (3.81)
Percent Occurrence for Average Year %									
New Orleans	2.96	2.16	1.74	1.44	1.08	0.92	0.56	0.37	0.21
Oklahoma City	2.04	1.49	1.23	0.81	0.57	0.46	0.20	0.15	0.11
Washington, D.C.	2.58	1.90	1.36	0.84	0.60	0.48	0.17	0.07	0.024
Portland, Oregon	1.84	1.34	1.09	0.57	0.35	0.28	0.11	0.05	0.016

precipitation at four stations that have prolonged periods of below freezing weather, such as Bismarck, North Dakota, revealed the following:

- (1) 99% to 100% of all precipitation that falls at rates equal to or exceeding  $0.12 \text{ inch h}^{-1}$  fall as rain and are encountered only at temperatures above freezing.
- (2) Roughly 85% of the precipitation falling at rates equal to or exceeding  $0.06 \text{ inch h}^{-1}$  are encountered at above freezing temperatures as rain, and the remaining 15% occur during the warmer months of the cold season and may be rain or snow.

Periods during which stations experience temperatures well below freezing can be determined from available climatic data.

#### 5.1.1.4 EXTREME RATES OF RAINFALL

(1) Five Year Expectancy—Climatic data are not available for computing the maximum rate of rainfall that can be expected to occur anywhere in the world in the next five years. It is necessary to relate the maximum rate of rainfall in a 5-year period in the United States, where data are available, to the worldwide expectancy.

Information on the maximum rainfall rates to be expected in the United States is contained in U.S. Weather Bureau Technical Paper No. 29 and in a report by Yarnell (1935). The highest rates of rainfall in the continental United States occur in a relatively narrow region bordering on the Gulf of Mexico. Table 5-4 gives maximum average rates over 1-min to 1-h time periods with a 5-year expectancy.

Although greater yearly rainfalls occur in some regions (for example, 70 to 130 inch in the Panama Canal Zone as compared to 57 inch at New Orleans), the 5-year expectancy on the Gulf Coast appears to be the right order of magnitude for the world. The measured 42-year maximum 5-min rainfall rate for the Canal Zone of  $10.9 \text{ inch h}^{-1}$  is only about 10% greater than the expectancy indicated for the same period along the Gulf Coast. Rates as high as  $16.1 \text{ inch h}^{-1}$  for a 5-min period have been observed at Pensacola, Florida in the past 22 years, but information on length of record is not available. Even Canal Zone rainfall amounts are far from the record 471 inch, the yearly average at Mt. Waialeale, Kauai, Hawaii. Maximum rates of fall for periods up to an hour, however, occur in thunderstorms that have physical limits to their rain production. In fact, during a heavy thunderstorm in Unionville, Md., 4 July 1956, a new world's record for the heaviest recorded one-min rainfall, 1.23 inch, was established. This is equivalent to a rate of  $73.80 \text{ inch h}^{-1}$ . Because thunderstorms occurring in tropical maritime air over the United States are as severe as over most places in the world, the Gulf Coast 5-year expectancy rates are probably at least 80% of the worldwide 5-year expectancy.

Table 5-4. Extreme Hourly Rates

Period (min)	Gulf Coast 5-year Expectancy		Worldwide All-Time (inch h <sup>-1</sup> )	(cm h <sup>-1</sup> )
	(inch h <sup>-1</sup> )	(cm h <sup>-1</sup> )		
1	15*	(38.1)*	112	(284)
5	7.2	(18.3)	48	(122)
10	6.0	(15.2)	36	( 91)
30	4.5	(11.4)	22	( 56)
60	3.2	( 8.1)	15	( 38)

\* estimated

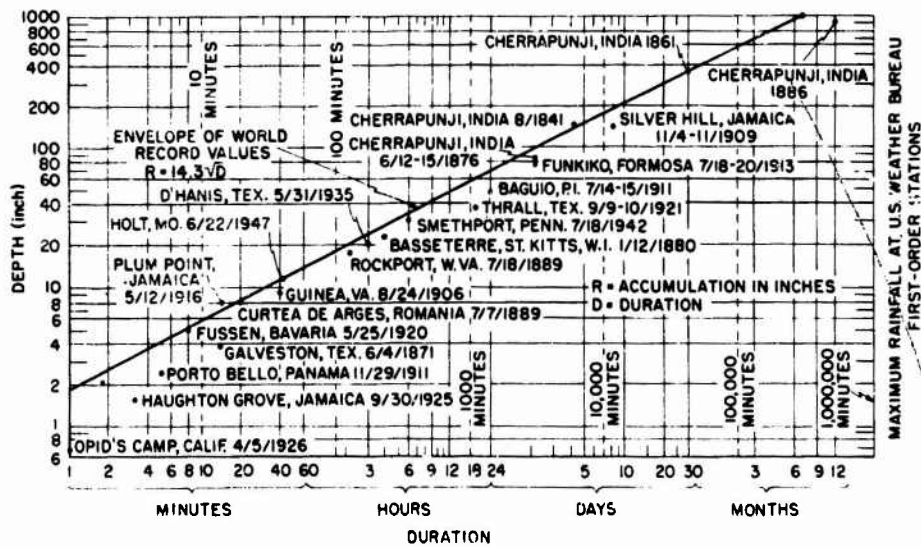


Figure 5-5. World Record Rainfalls and an Envelope of World Record Values.  
(After R. D. Fletcher and D. Sartos, Air Weather Service Tech. Rept. No. 105-81, 1951)

(2) All Time Worldwide Expectancy. In Figure 5-5, world record rainfalls for periods from one min to one year are plotted. From these data, which closely approximate a straight line on logarithmic scales, a worldwide all-time expectancy envelope for rainfall extremes over any one point is computed. This envelope, represented by  $R = 14.3 D^{1/2}$  (where R is the rainfall depth in inches and D the duration in hours), is shown in Figure 5-5. Values taken from this envelope for 1- to 60-min periods are tabulated in Table 5-4. The all time worldwide one-min rate is more than twice the 5-min rate.

#### 5.1.2 Hail

In generic terms, hail is precipitation in the form of round or irregular lumps of ice. In precise meteorological terminology, hail is defined as particles with a diameter of 5 mm or more; smaller particles are ice pellets. Ice pellets are, in turn, classified as sleet, which consists of generally transparent and globular grains of ice, or as small hail, generally translucent particles consisting of snow pellets (graupel or soft hail) encased in a thin layer of ice. Large hail has a diameter greater than 2 cm.

Large hail is formed only in well-developed thunderstorms whose cloud tops may sometimes extend above 50,000 feet; it is found only in, along, and under such storms. Small hail and soft hail are thought by some meteorologists to be an essential feature of all thunderstorms. However, ice particles less than 1-cm diameter, which may be present aloft in the cores of thunderstorms, are likely to melt completely before reaching the ground in a typical thunderstorm air mass. Although thunderstorms are most frequent in the tropics and subtropics, occurring up to 180 days per year in several places, hail is rarely found on the ground in the tropics. Hail that reaches the ground has a maximum frequency over mid-latitude mountainous and adjacent areas (such as Colorado, Wyoming, and Nebraska) where any given location may experience 5 to 10 hailstorms a year in an area where thunderstorms have a probability of occurring 40 to 50 days per year.

##### 5.1.2.1 HORIZONTAL EXTENT

The diameter of a well-developed thunderstorm cell of the type producing hail is of the order of 8 to 16 km. Diameters of the areas in which hail is encountered are generally 2 to 5 km. Encounters with several adjacent hailstorm cells in an area are probable, and hail paths on the ground nearly 16 km in width have been observed (Lemons, 1943).

### 5.1.2.2 VERTICAL EXTENT

Although hail can form only at altitudes above the 0°C level, it may be encountered in flights from the surface to very high altitudes. During the Thunderstorm Project (U.S. Weather Bureau, 1949), hail was found at all altitudes up to 26,000 feet, with a maximum occurrence at 15,000 to 16,000 feet in 10% of the traverses made in Florida and Ohio. Unfortunately, no aircraft data were obtained above 26,000 feet. Because the traverses necessarily covered a limited region of the thunderstorm, it is possible that hail was present somewhere in a large proportion of the thunderstorms. Also, the expectancy of hail reaching ground is only about 1 day per year in Florida, and 2 to 3 days per year in Ohio. Hail aloft should occur more frequently, and also at higher altitudes of maximum occurrence, over areas of greater probability of surface hail.

Analysis of 272 encounters by USAF planes in 1951 through 1959 (Foster, 1961) shows that the highest altitude at which large hail was encountered is 44,000 feet. More encounters (29%) occurred at 5000 through 10,000 feet than at any other 5000-foot segment. Over 40% of the encounters occurred above 20,000 feet, and 16% above 30,000 feet. All but three encounters above 20,000 feet were damaging to the aircraft, which suggests that there is a preponderance of large sizes, i. e. diameter 2 cm or greater, when hail is found in the upper part of the troposphere.

The probability of hail occurring at the ground increases with the height of the radar-echo tops of the associated thunderstorm. For about one-half of the New England thunderstorms with radar-echo tops above 50,000 feet, hail was reported at the ground (Donaldson, 1959). Hailstorms in Texas sometimes have echo tops above 60,000 feet. Some of these extremely high echo tops extend well above the cirrus anvil and penetrate a few thousand feet into the stratosphere. Because these giant storms must contain exceedingly high vertical velocities, the presence of hail above the tropopause in such storms is possible.

### 5.1.2.3 SIZE OF HAIL

#### (1) At the Ground

Extreme on record in U.S.A.: 5.4 inch (1.5 lb)

Occurrence of maximum size:

Diameter (inch)	Frequency (%)	Diameter (inch)	Frequency (%)
U.S.A. (176 cases with hailstones 1/2 inch or larger)		3.0 to 3.4	4
0.50 to 0.74	39	3.5 to 3.9	1
0.75 to 0.90	20	4 or more	1
1.0 to 1.4	14	India (597 cases)	
1.5 to 1.9	11	less than 0.2	27
2.0 to 2.4	6	0.2 to 1.2	51
2.5 to 2.9	4	greater than 1.2	22

Within the United States, hail sizes are larger in the lee of the Rocky Mountains than in the eastern states. In 829 reports covering a ten-year period in and near Denver, Colorado, the most frequent diameter of the largest hailstones was  $1/2$  inch; about one-third of the reports gave maximum hailstone diameters of at least  $3/4$  inch (Beckwith, 1960). In New England, 472 reports over a 5-year period show that the most frequent diameter of the largest hailstones is only  $1/4$  inch. About one-fourth of the reports, however, mentioned hailstones of at least  $3/4$  inch (Chmela, 1960).

(2) At Flight Altitudes. Adequate information on the size of hail at flight altitudes is not available; pilots generally avoid thunderstorms, especially violent ones capable of hail production. Also, when in flight it is difficult to estimate the size of hail. Two studies, however, give some indication of the altitudes and frequency of occurrence of large, damaging hailstones. A study of DC-3 flights (ceiling 12,000 ft.) on the Chicago-Denver air route shows that hailstones, 1 inch or larger, were encountered in one out of every 800 thunderstorm penetrations. In about half of these encounters, the maximum diameters exceeded 2 inch; in 10% of the cases, the hailstones were larger than 3 inch. Extremely large hail has been encountered even at high flight altitudes (Foster, 1961). Five-inch hail has been reported up to 29,500 feet, four-inch hail at 31,000 feet, and three-inch hail at 37,000 feet.

## 5.2 DISTRIBUTIONS OF PRECIPITATION, by R. Dyer

Precipitation parameters vary appreciably with type of storm, geographic location, and even from storm to storm, and for this reason, no model storms are presented in this section. However, individual profiles or averages that are derived from observations at several locations are given and, wherever possible, the applicability and representativeness of the data are indicated. Great care must be taken in extrapolating the results to geographical regions that are characterized by a climatology which differs from the climatology of the region from which the data were derived.

### 5.2.1 Raindrop Size Distributions

Numerous equations have been proposed to express the size distribution of raindrops measured at the ground as a function of rainfall rate. The most universally applicable distribution seems to be the log-normal. (A log-normal distribution has the same form as the normal distribution except that, instead of  $x$ , the variable is  $\log x$ ; consequently the logarithms of  $x$  are normally distributed.)

However, the log-normal (and approximations to it, such as the incomplete gamma function) is cumbersome to use, and does not yield readily integrable expressions. For this reason, exponential distributions of the form

$$N_D = N_0 e^{-\Lambda D} \quad (5-1)$$

are most commonly used;  $N_D dD$  is the number of drops per unit volume with diameters between  $D$  and  $D + dD$ ,  $N_0$  is the value of  $N_D$  where the curve crosses the  $D = 0$  axis, and  $\Lambda$  is a parameter which depends on the type and intensity of the precipitation.

Equation 5-1 was derived for stratiform-type rainfall originating as snow (Marshall and Palmer, 1948). The exponential function usually overestimates the number concentrations of the smaller drops. Since there is a physical limit of 5 to 6 mm diameter for raindrops, exponential functions also usually overestimate the number of large drops. In fact, for the types of rain which Marshall and Palmer considered, Eq. 5-1 should be used only for number concentrations of drops having diameters between 0.75 and 2.25 mm at rainfall rates of about  $1 \text{ mm h}^{-1}$ , between 1.25 and 3 mm for rainfall rates near  $5 \text{ mm h}^{-1}$ , and between 1.5 and 4.5 mm for rainfall rates above  $25 \text{ mm h}^{-1}$ . Within these size ranges, however, the Marshall-Palmer distribution provides reasonable average number concentrations.

The total liquid water content,  $M$ , the radar reflectivity,  $Z$ , and the median volume diameter,  $D_0$ , can all be expressed in terms of  $N_0 (\text{mm}^{-1} \text{ m}^{-3})$  and  $\Lambda (\text{mm}^{-1})$  by the appropriate integration of Eq. 5-1 as follows:

$$D_0 = 3.67/\Lambda \quad (\text{mm}) \quad (5-2)$$

$$M = 10^{-3} \pi (\rho N_0 / \Lambda^4) \quad (\text{g m}^{-3}) \quad (5-3)$$

$$Z = 720 N_0 / \Lambda^7 \quad (\text{mm}^6 \text{ m}^{-3}) \quad (5-4)$$

In Eq. (5-3),  $\rho$  is the density of water in  $\text{g cm}^{-3}$ .

Rainfall rate is a comparatively easy quantity to measure, and many empirical relations have been proposed of the form  $Z$  (or  $M$ ,  $D_0$ ,  $N_0$ ,  $\Lambda$ ) =  $A R^B$ , where  $R$  is the precipitation rate in millimeters per hour and  $A$  and  $B$  are constants. The relations differ in small but significant degrees, according to the location and type of precipitation.

Table 5-5 and Figures 5-6, 5-7, and 5-8 summarize the results of several investigations. The shaded area of Figure 5-6 encompasses the range of

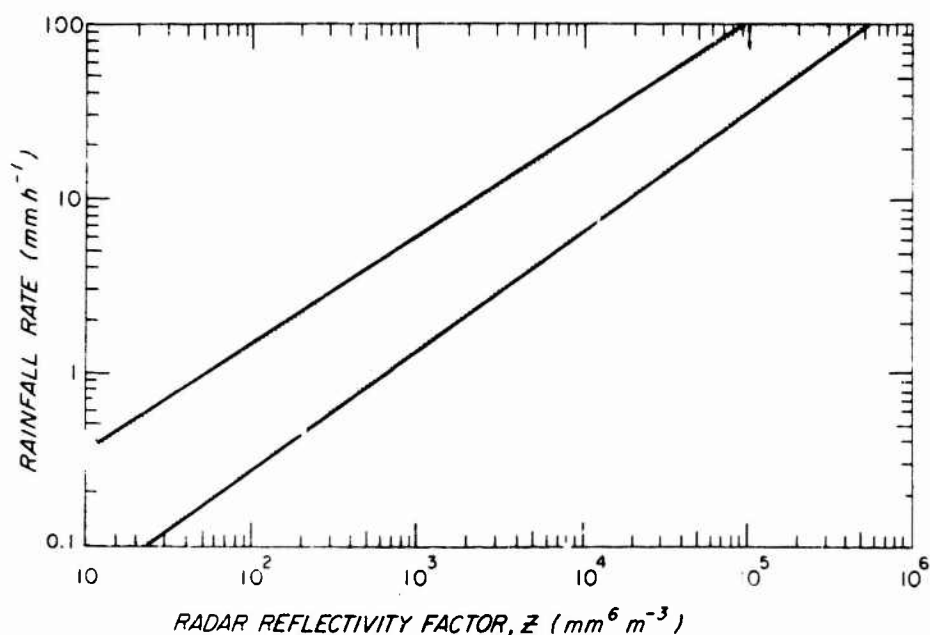


Figure 5-6. Radar Reflectivity Factor Versus Rainfall Rate. The shaded area is in the range of the measured relations

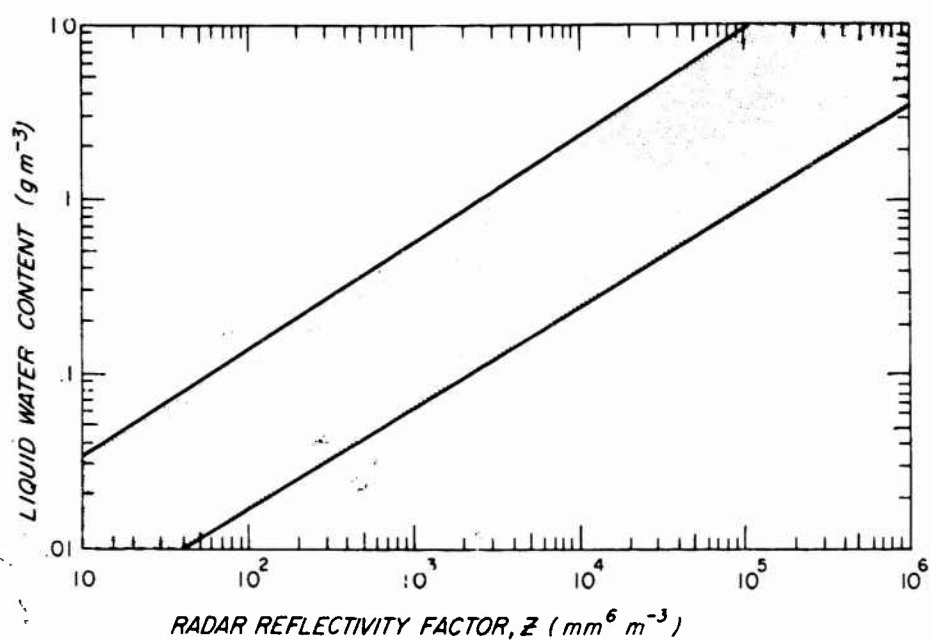


Figure 5-7. Radar Reflectivity Factor Versus Liquid Water Content of Precipitation. The shaded area is the range of observed relations

Table 5-5. Characteristics of Precipitation at Various Locations Derived from Raindrop-size Distributions Measured Near the Ground

Source	Location	Type of Precipitation	$N_0$ ( $\text{mm}^{-1} \text{m}^{-3}$ )	$\Lambda$ ( $\text{mm}^{-1}$ )	$D_0$ (mm)
Marshall and Palmer (1948)	Ottawa	Continuous	8,000	$4.1R^{-0.21}$	$*.90R^{0.21}$
Best (1950)	Ynyslas (Wales)	Average	8,600	$*3.1R^{-0.20}$	$1.2R^{0.20}$
		Average	1,200	$*2.8R^{-0.21}$	$1.32R^{0.21}$
Ramana Murty and Gupta (1959)	India	Monsoon Rain	$*7,500R^{-0.25}$	$4.5R^{-0.27}$	$0.81R^{0.27}$
		Orographic	$*1,500R^{0.23}$	$3.2R^{-0.17}$	$1.14R^{0.17}$
Sivaramakrishnan (1961)	India	Thunderstorm		$*4.5R^{-0.29}$	$.82R^{0.29}$
		Melting Band		$*5.2R^{-0.29}$	$.71R^{0.29}$
		Non-Freezing		$*7.5R^{-0.50}$	$.49R^{0.50}$
Fujiwara (1965)	Florida	Thunderstorm	1,100	$*2.9R^{-0.23}$	$1.28R^{0.23}$
		Showers		$*4.4R^{-0.44}$	$0.84R^{0.44}$
		Continuous			
Joss et al. (1968)	Switzerland	Drizzle	30,000	$5.7R^{-0.21}$	$*.64R^{0.21}$
		Continuous	7,000	$4.1R^{-0.21}$	$*.90R^{0.21}$
		Thunderstorm	1,400	$3.0R^{-0.21}$	$*1.22R^{0.21}$

\* Indicates relationship derived from measured characteristics, the Z-R relation, and Eqs. (5-2), (5-3), and (5-4).

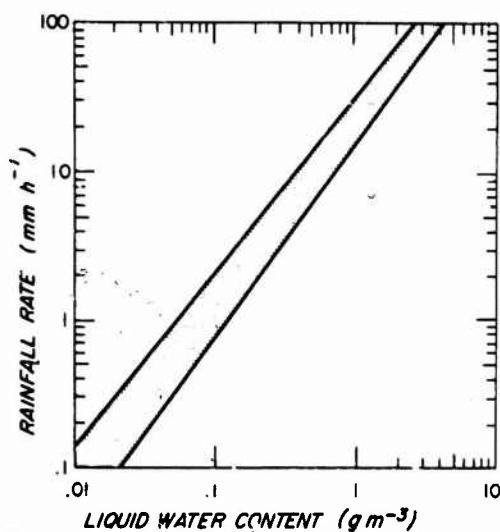


Figure 5-8. Liquid Water Content of Precipitation Versus Rainfall Rate

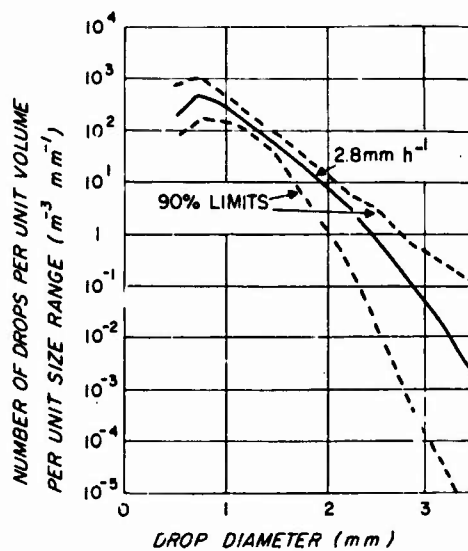


Figure 5-9. Surface Raindrop-size Distribution for a Rainfall Rate of  $2.8 \text{ mm h}^{-1}$

measured relations between radar reflectivity and rainfall rates, and illustrates the variability that can be encountered. Figure 5-7 expresses the same data in terms of radar reflectivity versus liquid water content. If rainfall rate is the measured quantity, Figure 5-8 can be used to find the expected range of liquid water content. Although there are wide variations from storm to storm,  $N_0 = 8000$  ( $\text{mm}^{-1} \text{m}^{-3}$ ) and  $\Lambda = 4.1R^{-0.21}$  ( $\text{mm}^{-1}$ ) may yield fairly representative values for many purposes.

Much of the variability in drop-size measurements is attributable to the small volumes sampled by the sensing equipment (Joss and Waldvogel, 1969). Estimates of the drop-size distribution within large volumes (in excess of  $3 \times 10^4 \text{ m}^3$ ) have been obtained using Doppler radar by averaging the measurements over height intervals from 525 to 975 m directly above the radar (Caton, 1966). Figure 5-9 shows median concentrations for each size measured in a group of 19 rains. The median rainfall rate in the entire set of observations is  $2.8 \text{ mm h}^{-1}$ , although the rates for the 19 cases varied from 2.0 to  $4.0 \text{ mm h}^{-1}$ . The variability of the drop concentrations within this group of 19 rains is also illustrated in Figure 5-9; the dashed curves show the limits within which approximately 90 per cent of the values lie (the lowest and the highest concentrations at each size being omitted). It can be seen that, even with large sampling volumes and with rainfall rates varying by only a factor of two, the drop concentrations may vary by at least an order of magnitude; for drops greater than 3 mm diameter, the variability is about three orders of magnitude. It should be noted, however, that the variability of concentrations of drops between 1.0 and 1.5 mm diameter is quite small and that these drops contribute most to the precipitation rate. In general, the drop-size distributions observed with radar in England (Caton, 1966) had fewer large drops than the distributions observed by an optical sensing instrument at various locations in the United States (Mueller and Sims, 1966).

Widespread stratiform storms generally show very little change in the radar reflectivity between the surface and the base of the melting level. For this reason, the distributions for stratiform rain shown in Figures 5-9 and Table 5-5 are approximately applicable from the surface to the melting level.

### 5.2.2 Snowflakes

Gunn and Marshall (1958) found that an exponential law similar to Eq. 5-1 was applicable to the size distribution of aggregate snowflakes. The spectral parameters in snow are related to the precipitation rate by:

$$N_0 = 3.8 \times 10^3 R^{-0.87} \quad (\text{mm}^{-1} \text{m}^{-3}) \quad (5-5)$$

$$\Lambda = 2.55R^{-0.48} \quad (\text{mm}^{-1}) \quad (5-6)$$

where  $R$  is precipitation rate in millimeters of water per hour. For snowflakes, the diameter  $D$  in Eq. 5-1 refers to the melted spherical diameter of the snowflake. Atlas (1964), who described the work of investigators in Japan and Canada, indicated the following: (1) the distribution of the dry snow high in the storm system has a steep exponential slope; (2) aggregation above the melting level causes a great reduction in the slope by increasing the number of large particles and decreasing the number of small ones; and (3) breakup upon melting establishes the final drop spectrum with an intermediate slope.

More recently, Ohtake (1969) made measurements in Japan and on Douglas Island, Alaska. In the storms studied, he found that the sizes of the melted snowflakes (in terms of their equivalent mass) were conserved as the snow changed to rain through the melting level. This indicates that a snowflake melts into a single raindrop without breaking up in the melting level. (The spatial distribution of the snow and the rain, however, is different because of the difference in fall speed of the two types of hydrometeors.) For plane dendritic snowflakes, Ohtake found that the distributions generally were consistent with the distributions given in Eqs. 5-5 and 5-6. For needle snow crystals, the melted spatial distributions generally were similar to the distribution given by Eq. 5-1.

Comparing the findings of Atlas and Ohtake, it appears that aggregation of snow and breakup upon melting occurs in many, but not all, instances. The difference may lie in the slope of the temperature profile in the melting layer, i.e. a large increase in temperature with decreasing height could cause rapid melting with no aggregation and no subsequent shattering. This explanation is speculative, however, and further observations are needed.

### 5.2.3 Distribution of Precipitation with Height

The vertical distribution of precipitation parameters can be inferred from the distribution of radar reflectivity, using appropriate relations indicated in Figures 5-6, 5-7, and 5-8. Studies for the Montreal area indicate that the vertical distribution of rainfall intensity depends on whether the precipitation is continuous or showery (Hamilton, 1964). Figure 5-10 shows a typical profile of precipitation intensity within a continuous storm in the Montreal area on 13 August 1963. The precipitation at higher levels is in the form of snow, but the same conversion from the radar reflectivity to precipitation rate was used for both rain and snow (Hamilton, 1966). A point on a curve gives the percentage of the area which exceeds the precipitation rate of the designated curve. Storms in which snow occurs at the surface will generally have distributions of this sort but the intensities will be lower. Figure 5-11 shows the distribution within a region containing moderately severe showers obtained on 2 July 1963 in the Montreal area.

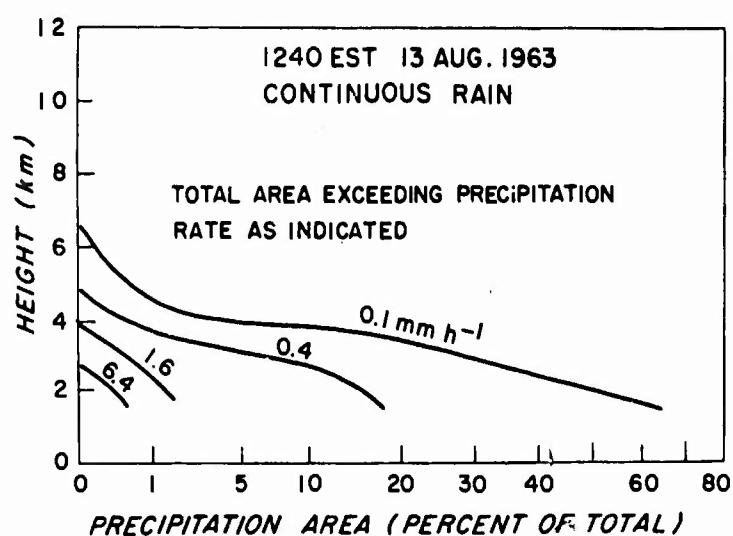


Figure 5-10. Vertical Profile of the Total Area of Precipitation Exceeding Given Intensities of Continuous Rain. The abscissa is per cent of the area scanned between radar ranges of 35 and 150 km which contains precipitation. (After Hamilton, 1964)

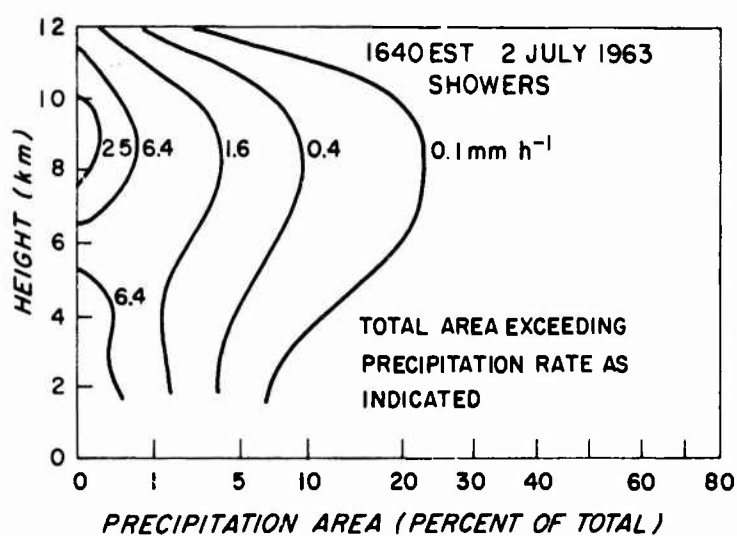


Figure 5-11. Vertical Profile of the Total Area of Precipitation Exceeding Given Intensities of Heavy Showers. (After Hamilton, 1964)

Although Figures 5-10 and 5-11 are only applicable for a specific time, the general features illustrated are typical for the types of precipitation considered.

The great difference between the two examples of Figures 5-10 and 5-11 is that in the heavy shower situation there is an accumulation of precipitation aloft at 9 km, whereas in the continuous rain the precipitation is growing continuously throughout its descent. The accumulation of rather large quantities of precipitation aloft within the strong updrafts of severe convective storms is also evident from a theoretical consideration of the development of precipitation in a model convective cell (Kessler, 1967).

Hamilton (1966) also found that the bulk of the precipitation aloft in heavy showers is due to the moderate precipitation. The large area of light precipitation commonly found at the upper levels in heavy showers is associated with the anvil and rarely contributes significantly to the total. The heaviest precipitation aloft usually covers such a small area that it too only contributes a minor fraction to the total.

Holtz (1968) has derived a three dimensional model of a thunderstorm by using radar records and considering the life cycle of a summer storm in the Montreal area. The three-dimensional distribution of precipitation varies systematically throughout the storm's life-cycle as the total mass varies. Holtz also observed that at each moment the total fallout-rate was proportional to the total mass of precipitation aloft and that most of the precipitation was generated in a short period.

Figure 5-12 shows a result of climatological studies of the distribution of precipitation aloft (Marshall et al, 1966). The original study included days with no precipitation as well as days on which some precipitation occurred. Therefore, the data were adjusted so that Figure 5-12 indicates the probability of equalling or exceeding a given intensity, provided there is a storm in progress somewhere within the  $69,000 \text{ km}^2$  area of coverage; the data refer to a summer season in the vicinity of Montreal. The curves in Figure 5-12 show that, on a seasonal basis, the probability of a given rainfall rate or precipitation content decreases with height except for the very highest precipitation rate. The data of Figure 5-12 also indicate that the bulk of the precipitation throughout the summer season in the Montreal area has a vertical profile similar to that of Figure 5-10 in contrast to the showery profile illustrated in Figure 5-11.

The results in Figures 5-10, 5-11, and 5-12 were derived from radar data and consequently are applicable only for particles which have already grown to precipitation size. Substantial cloud water contents may co-exist with the precipitation water contents. For example, in steady stratiform precipitation, the mass of cloud water per unit volume may be two or three times that of rain in the zone just below the melting level, especially in light precipitation.

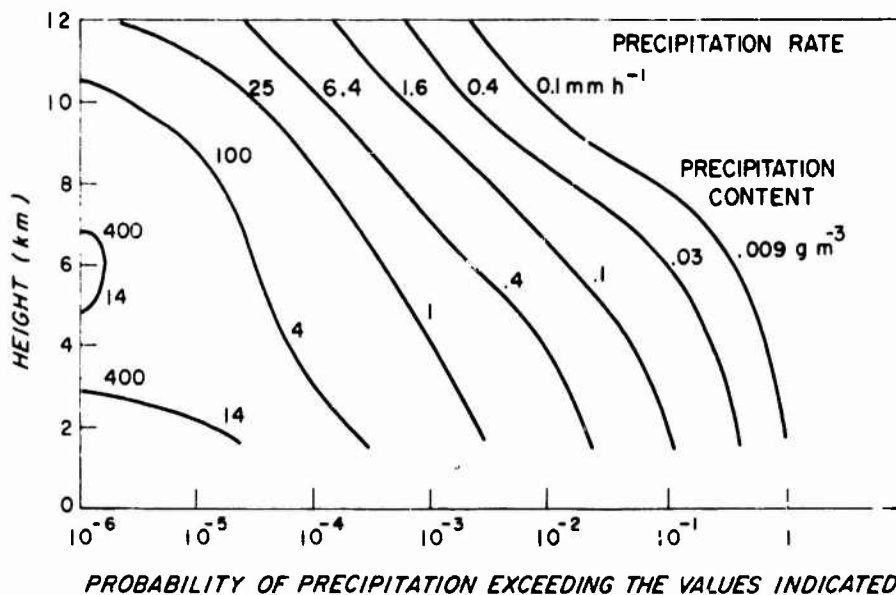


Figure 5-12. Probability of Equalling or Exceeding Given Precipitation Intensities When a Storm Is in Progress Within Radar Coverage of Montreal, Canada. Data obtained as a function of height are for one summer season. (After Marshall et al., 1966)

Unfortunately, the water contents of clouds within storm systems have not been mapped to the same extent as the water contents of precipitations. Kessler (1967) and Wexler and Atlas (1958), investigated storm models theoretically and computed the distribution of cloud water content for both convective and stratiform precipitation. Their results show that the distribution of cloud water content depends markedly on the type of the precipitation and the stage of development of the storm.

#### 5.2.4 Extreme Values of Liquid Water Content

Measurements of the maximum concentration of liquid water in severe convective storms have not been made on a systematic basis. Isolated reports of concentrations as high as  $30 \text{ g m}^{-3}$  (Sulakvelidze et al., 1965) and even  $44 \text{ g m}^{-3}$  (Roys and Kessler, 1966) are found in the literature. (There have been occasions when investigators have suspected the occurrence of abnormally high concentrations, but lacked the equipment for measuring them.) Considering many aspects of the storm, Roys and Kessler could not find evidence which indicated that the measured concentration of  $44 \text{ g m}^{-3}$  should be rejected or accepted. Omitting the value of  $44 \text{ g m}^{-3}$ , their 27 measurements of the maximum liquid water content

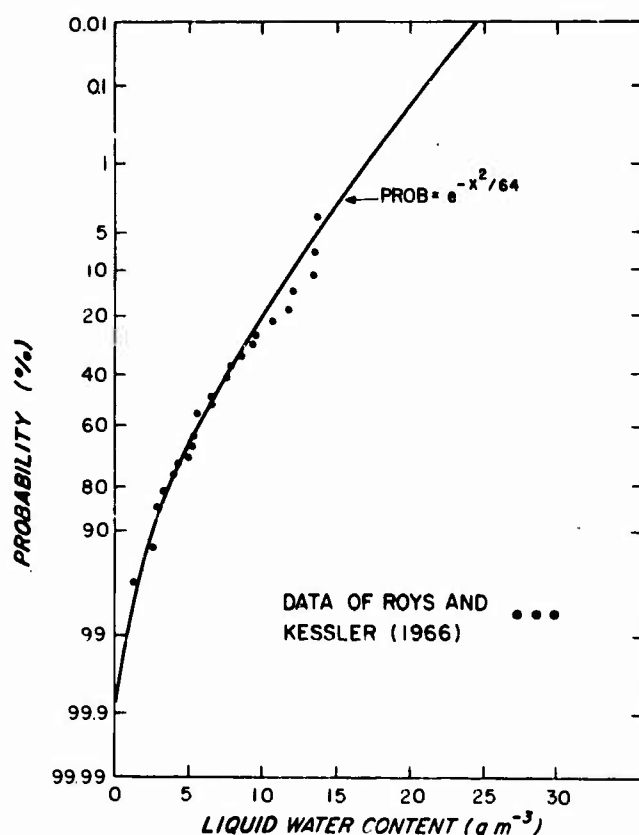


Figure 5-13. Probabilities of Water Content Within Oklahoma Thunderstorms. The ordinate gives the probability that the maximum water content will equal or exceed the value given by the abscissa

in Oklahoma thunderstorms fit very well the distribution illustrated in Figure 5-13. According to this distribution, the probability that the maximum water content,  $M$ , in an Oklahoma thunderstorm will exceed a given value,  $x$ , is

$$P(M > x) = \exp(-x^2/64) \quad (5-7)$$

where  $M$  and  $x$  are in grams per cubic meter.

It is dangerous to extrapolate from such a small sample. Nevertheless, the actual occurrence of extreme values of liquid water concentrations probably follows the general shape of Figures 5-13 with possible modification of the constants in the distribution function. Figure 5-13 indicates that 75% of Oklahoma thunderstorms have maximum liquid water contents exceeding  $4.3 \text{ g m}^{-3}$ , and that

liquid water contents in excess of  $9.4 \text{ g m}^{-3}$  occur in only 25% of the storms. Substitution into Eq. 5-7 shows that values of  $30 \text{ g m}^{-3}$  or higher are literally "one in a million" occurrences in Oklahoma thunderstorms, and the occurrence of a value of  $44 \text{ g m}^{-3}$  has a probability of  $10^{-12}$ .

It is of interest to compare these extreme values of water content to the water content corresponding to a record rainfall rate. Over a 1 min. interval, the world record rainfall amount is 1.23 inches (3.1 cm); this fell at Unionville, Maryland in 1956 (Seamon and Bartlett, 1956). Assuming a Marshall-Palmer distribution, the above rainfall rate corresponds to a liquid water content of approximately  $55 \text{ g m}^{-3}$ . Consequently, extremely large values of water content (e. g. greater than  $30 \text{ g m}^{-3}$ ) may occur on rare occasions either at the surface or aloft in severe thunderstorms.

### 5.3 CLOUDS, by A.J. Kantor

This section gives information on clouds and the types and limitations of available cloud data. Examples of a few of the standardized cloud summaries prepared on a routine basis by national weather services are provided. Information is also provided on the maximum water content likely to be encountered in clouds from which precipitation is not occurring. Because frequently there are wide variations in the cloud distribution among stations only a few miles apart, particularly in the lower levels, geographic frequency-distributions of clouds below 30,000 feet (9 km) are not provided. New data on high-altitude clouds are presented.

It is recommended that information required for specific design problems should be obtained from meteorologists familiar with the variability and limitations of the data; a detailed description of the problem and the proposed method of application should be provided.

The cloud distribution over a particular region generally is more uniform above 20,000 feet (6 km) than at lower levels where topographical effects can cause wide variations over stations located a few miles apart. In addition, surface visual observations are of limited value for defining frequency distributions of clouds at various levels. Consequently, information in this section is based primarily on aircraft and radar observations, which may be more accurate but frequently are not available on a synoptic basis.

#### 5.3.1 Surface Observations

Cloud observations taken regularly by observers at surface weather stations throughout the world usually contain the following information:

- (1) Visual estimate of total amount of sky covered by clouds ;
- (2) Cloud ceiling, which is the estimated or measured height-above ground of the lowest layer of clouds that cover more than one half of the sky; and
- (3) Visual estimates or measurements of amount and height of bases of individual cloud types or layers.

Because low clouds frequently obscure high clouds, it is often impossible to obtain accurate information on the distribution of clouds at higher levels from visual observations at the surface. Studies of the accuracy of visual cloud observations show that errors occur in estimating cloud cover such that cloud amounts are consistently overestimated for conditions other than overcast or clear; the bias is greatest when the sky is  $3/8$  to  $5/8$  covered. For visual estimations of cloud heights, the average error ranges from 1000 feet (300 m) for clouds near 2500 feet (760 m), to 5000 feet (1.5 km) for clouds with bases near 23,000 feet (7 km). At many observation points, however, particularly airport stations, ceiling heights measured with ceilometers, clinometers, or balloons are available. These height measurements are much more accurate than heights based on visual estimates.

Observed values for a particular time give amount of sky covered but not the cloud distribution. For example, if  $4/8$  cloud cover is reported, one large cloud formation may cover half of the sky or small individual cloud cells may be equally distributed over the entire sky. At present, there is no indirect way of obtaining the geometry of clouds in the sky from the reported standard observations.

#### 5.3.1.1 SUMMARIES OF SURFACE OBSERVATIONS

Tabulations of surface observations of clouds are available for stations in most areas of the world. Summaries similar to Tables 5-6 and 5-7, giving the frequency of occurrence of various amounts of cloud cover during different times of the day for each month of the year, are available for most stations. The type of summary given in Table 5-7 is prepared monthly by the U.S. Weather Bureau for each first-order weather station in the United States. Numerous studies providing the frequency of occurrence of various ceiling heights for various times of the day, seasons, synoptic situations, and so on, are available for airport stations. Table 5-8, for example, shows the frequency of various ceiling heights during each month of the year at Washington, D.C. In addition to the conventional summaries, other summaries and studies are available, or can be prepared, that provide specific types of information on cloud distribution at individual stations; for example, see Spreen and Solomon (1958).

Table 5-6. Cloud Cover Data for London, England

Hour	Mean Number of Clear (0 to 3 Tenths Cloud Cover) Days												
	Jan.	Feb.	March	Apr	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
0700	5	5	7	6	6	8	7	7	7	6	5	6	75
1300	5	4	5	3	3	4	3	3	3	4	4	4	45
1800	7	6	8	5	6	7	4	8	7	8	8	9	83
Hour	Mean Number of Cloudy (9 to 10 Tenths Cloud Cover) Days												
	Jan.	Feb.	March	Apr	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
0700	22	18	19	18	18	15	16	17	17	17	20	21	218
1300	27	27	27	18	19	15	20	14	16	18	20	22	186
1800	19	17	15	16	16	12	15	12	14	15	17	18	210

Table 5-7. Hourly Occurrences of Various Amounts of Sky Cover at Duluth, Minnesota During November, 1950

Hour	Cloud Cover		
	0 to 3/10	4/10 to 7/10	8/10 to 1
0100	11	1	18
0200	11	0	19
0300	10	2	18
0400	9	3	18
0500	5	4	21
0600	10	0	20
0700	6	2	22
0800	7	2	21
0900	9	3	18
1000	9	3	18
1100	7	5	18
1200	8	1	21
1300	8	2	20
1400	8	2	20
1500	5	5	20
1600	8	2	20
1700	10	3	17
1800	10	2	18
1900	9	1	20
2000	12	0	18
2100	11	2	17
2200	12	1	17
2300	11	1	18
2400	9	1	20

Table 5-8. Percentage Frequency of Occurrence of Various Ceiling Heights at Washington, D. C. (From U. S. Weather Bureau Report 1945, "Normal Flying Weather for the United States")

Ceiling Ht. (ft)	Dec.	Jan.	Feb.	Winter	Mar.	Apr.	May	Spring	June	July	Aug.	Summer	Sept.	Oct.	Nov.	Fall	Annual Mean
0-300	3.1	5.7	2.8	3.9	1.9	1.0	0.8	1.2	0.4	0.5	0.5	0.5	2.1	1.6	2.3	2.0	1.9
301-600	4.6	5.5	4.4	4.8	4.0	3.4	2.4	3.3	1.9	2.0	2.2	2.0	3.8	2.8	3.9	3.5	3.4
601-1000	3.6	4.7	4.0	4.1	5.2	5.6	4.1	5.0	2.9	5.0	3.8	3.9	4.0	3.1	4.7	3.9	4.2
1001-2000	4.6	5.4	4.3	4.8	5.1	4.5	4.6	4.7	4.7	4.7	4.5	4.6	4.7	4.1	5.1	4.6	4.7
2001-5000	13.6	14.0	11.7	13.1	15.2	12.2	10.7	12.7	9.6	9.5	9.6	9.6	9.8	10.0	13.4	11.1	11.6
5000-9750	10.2	10.0	9.5	9.9	9.6	10.0	9.6	9.7	7.1	6.0	8.0	7.0	6.1	7.2	9.0	7.4	9.5
Over 9750	60.3	54.7	63.4	59.5	59.0	63.2	67.9	63.4	73.3	72.5	71.5	72.4	69.5	71.1	61.5	67.4	65.7

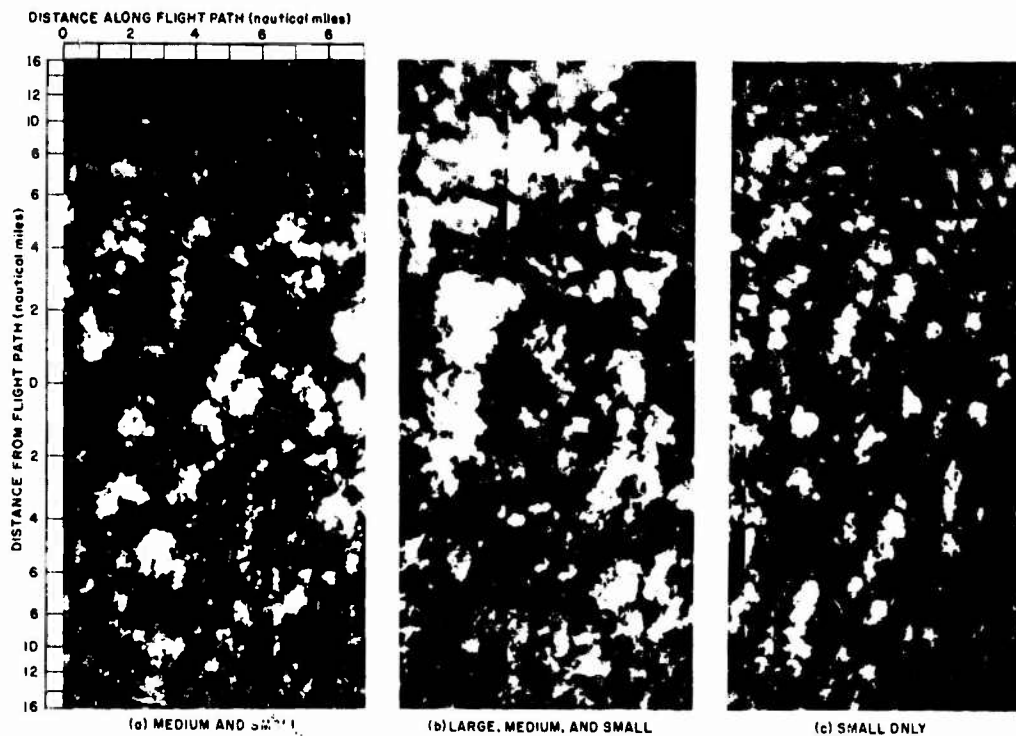


Figure 5-14. Typical Distribution of Cumulus Cloud Types as Shown by Photograph Taken From U-2 Aircraft. (Stanford Research Institute)

### 5.3.1.2 LIMITATIONS IN THE USE OF SUMMARIES FOR A PARTICULAR STATION

There can be considerable variation in the frequency of occurrence of given cloud amounts and ceiling heights between stations located within several miles of each other. Because local topographical effects are the primary cause of such variations, extreme caution must be used in applying climatological data on clouds for one or several stations to an entire region, particularly in mountainous and coastal regions.

### 5.3.2 Aircraft and Radar Observations

Cloud observations taken by reconnaissance aircraft are available over a few areas and routes. Summaries of these observations usually are available only in reports and studies related to specific problems such as aircraft icing, turbulence, and thunderstorm activity; they provide information on the frequency of encountering clouds at particular flight levels. Intervening cloud layers, however, often obscure the cloud distribution at other levels. High-altitude aircraft also can provide cloud photographs, such as Figure 5-14, from which dimensions and distributions of cumulus clouds can be estimated. Weather satellite photographs are providing information on the distribution of clouds over large areas of the earth. From the accumulation of such data, regional and global cloud climatologies are being developed. Radar observations give information on cloud distribution at various levels, but until recently these data have been limited to intermittent observations at a few stations.

### 5.3.3 Vertical Extent of Cirrus and Convective Clouds

In studies of cirrus clouds over the British Isles and Canada, aircraft observations indicate that a definite relationship exists between the height of the tropopause and the tops of cirrus clouds. Table 5-9, based on 151 aircraft observations of cirrus clouds in the vicinity of the British Isles (James, 1957) and more than 2000 RCAF reports over Canada (Clodman, 1957), gives the frequency distribution of cirrus tops relative to the tropopause. The occurrence of a maximum of cirrus tops just below the tropopause over both regions is consistent with other results. Although cirrus clouds are observed above the tropopause, the evidence indicates that the probability of encountering extensive cirrus cloud formations above the tropopause is small.

The probability of encountering convective clouds above the tropopause is relatively small, but it is larger than it was once thought to be. Depending upon location and time, the penetrations of the tropopause by convective clouds can be significant. Figure 5-15 shows mean monthly frequencies of penetrations greater

Table 5-9. Distribution of Cirrus Tops Relative to the Tropopause

Distance from Tropopause (ft)		Frequency of Occurrence (%)
BRITISH ISLES		
> 4000	above	10
4000 to 0	above	10
0 to 4000	below	50
4000 to 8000	below	16
> 8000	below	14
CANADA		
> 5000	above	1
5000 to 0	above	12
0 to 5000	below	52
5000 to 10,000	below	23
< 10,000	below	12

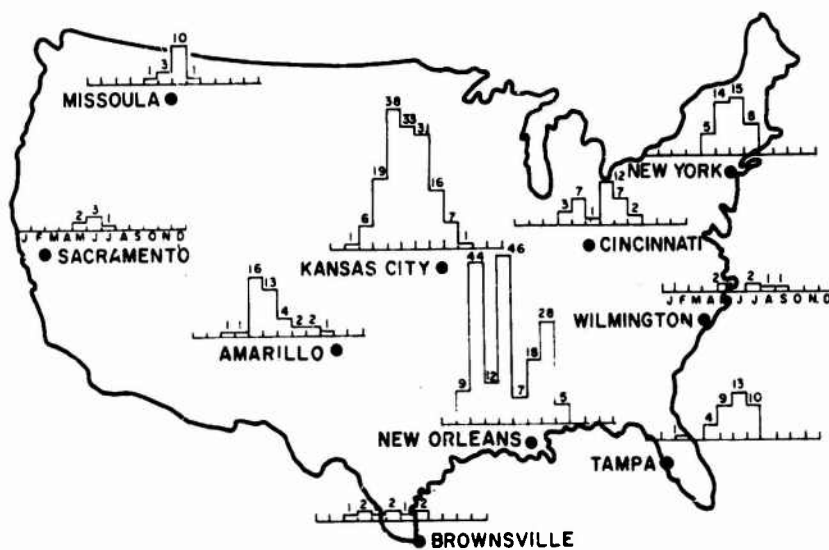


Figure 5-15. Average Monthly Tropopause Penetrations by Thunderstorms, 1961-1964. (From Long et al, 1965)

Table 5-10. Mean Seasonal Heights of the Tropopause

Latitude	Altitude			
	Dec. -Feb. (ft)	Mar. -May (ft)	June-Aug. (ft)	Sept. -Nov. (ft)
60° to 80° N	26,000	28,000	34,000	30,000
50° to 60° N	34,000	34,000	38,000	34,000
40° to 50° N	36,000	38,000	44,000	38,000
30° to 40° N	45,000	45,000	48,000	45,000
10° to 30° N	55,000	52,000	52,000	52,000

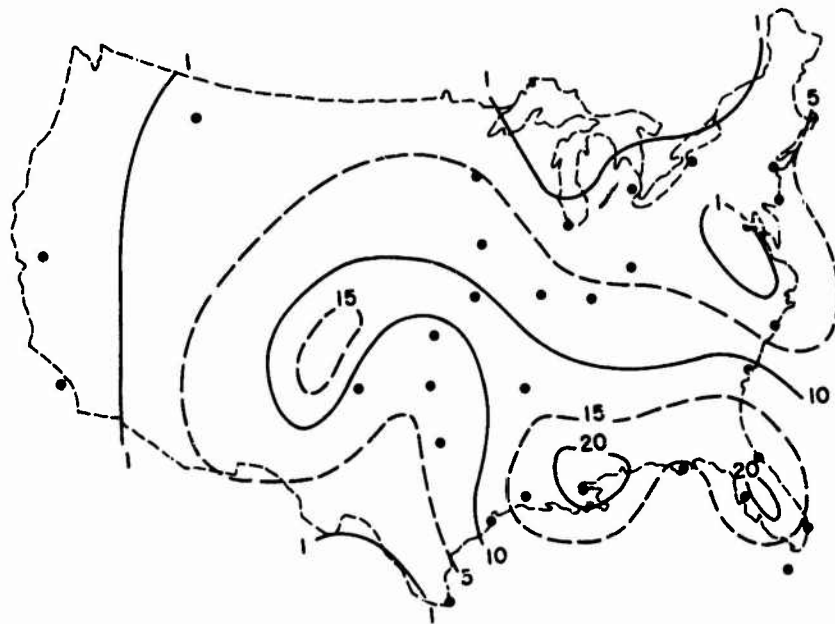


Figure 5-16. Probability (%) of Precipitation Echoes at 45,000 to 50,000 feet (13.5 to 15 km) in July. (From Grantham and Kantor, 1967)

than 5000 feet (1.5 km) for 10 locations in the United States. Both seasonal and geographic differences are apparent in the figure, which is based on U.S. Weather Bureau data obtained from radar sets operating continuously at each location.

Because there are seasonal, latitudinal, and daily variations in the height of the tropopause, both the latitude and season of the year must be considered in planning minimum flight altitudes above the tropopause. Table 5-10 gives the mean seasonal heights of the tropopause in the Northern Hemisphere; however, mean seasonal heights may be several thousand feet higher than indicated in Table 5-10 on the east side of semistationary lows such as the Icelandic and Aleutian lows during the winter and spring months.

In middle latitudes, the day-to-day variations in the height of the tropopause exceeds the seasonal variations; large variations in height occur as a result of horizontal oscillations in the tropopause. The arctic tropopause from the north is brought southward in the rear, and the tropical tropopause from the south is projected northward in advance of well-developed migratory cyclones. Although data are not sufficient to establish exact limits, available data indicate that in middle latitudes ( $40^{\circ}$  to  $60^{\circ}$ N) the tropopause can fluctuate between about 20,000 and 50,000 feet (6 and 15 km). North of  $60^{\circ}$  and south of  $30^{\circ}$  latitude, the range is much smaller, the order of 3000 to 6000 feet (900 to 1800 m) around the seasonal mean heights: 26,000 feet (8 km) in winter and 34,000 feet (10 km) in summer north of  $60^{\circ}$  latitude; and 52,000 feet (16 km) in summer and 55,000 feet (17 km) in winter south of  $30^{\circ}$ N.

Radar observations also provide first estimates of the probability of high altitude convective clouds that contain precipitation-size particles. Figure 5-16, as an example, depicts the estimated probability of encountering a convective cloud over the United States in July at 45,000 to 50,000 feet (13.5 to 15 km) altitude within 100 miles (160 km) of a given location. Examination of three years of data (1962 through 1964) from a network of 31 continuously operated radar installations reveals that echoes have been detected from convective clouds up to at least 70,000 feet (21.5 km) in May, June and July, and 60,000 feet (18 km) in winter. Rough estimates of geographic, seasonal, and diurnal fluctuations from 35,000 to 60,000 feet (10.5 to 18 km) have been made (Grantham and Kantor, 1967) for these locations and are being extended to other regions of the world. Additional radar data are entering the inventory; for example, fixed beam vertically pointing radars designed to depict cloud structure as it crosses the radar beam for all altitudes up to 60,000 feet (18 km) are now being used at many U.S. Air Force stations around the Northern Hemisphere.

Table 5-11 summarizes the frequency and percent occurrence of radar echoes above 30,000 feet (9 km) by three-hour periods in July at Oklahoma City.

Table 5-11. Radar Echoes in July (1962-1964), Oklahoma City [Grantham and Kantor, 1967]

Altitude (10 <sup>2</sup> feet)	Local Standard Time															
	01-03		04-06		07-09		10-12		13-15		16-18		19-21		22-24	
	Freq.	%	Freq.	%	Freq.	%	Freq.	%	Freq.	%	Freq.	%	Freq.	%	Freq.	%
650 - 699													1	0.4		
600 - 649	1	0.4									1	0.4	1	0.4		
550 - 599	3	1.1	1	0.4			1	0.4	8	2.9	3	1.1	2	0.7		
500 - 549	10	3.6	4	1.4			2	0.7	20	7.2	22	8.1	8	2.9	4	1.4
450 - 499	12	4.3	9	3.2	4	1.5	4	1.5	32	11.6	48	17.6	19	6.9	13	4.7
400 - 449	23	8.3	22	7.9	9	3.3	12	4.4	52	18.8	62	22.8	37	13.4	26	9.4
350 - 399	32	11.6	40	14.4	15	5.5	16	5.9	61	22.1	85	31.3	47	17.0	37	13.4
300 - 349	52	18.8	64	23.1	50	18.2	32	11.8	81	29.3	103	37.9	76	27.5	47	17.0
Total Hours	277 h		277 h		274 h		271 h		276 h		272 h		276 h		277 h	

Table 5-12. Frequency With Which Clouds Were Encountered at Various Flight Levels Above 20,000 ft Over the U.S.

Altitude Level (ft)	Total Number of Observations*	Number of Observations in Clouds	Time in Clouds (%)
20,000-24,980	7257	422	5.8
25,000-29,990	5683	292	5.1
30,000-34,990	689	13	1.9
35,000-39,990	976	2	0.2
40,000-44,990	831	0	0
Above 45,000	0	0	0

\* These data are listed in terms of number of observations rather than time in hours because the conditions were not recorded continuously but as discrete observations at intervals of approximately one half hour.

In this sample table a diurnal maximum occurrence and maximum altitude of echoes between 1600 and 2100 hour (local standard time), and a minimum between 0700 and 0900 hour (local standard time) is displayed. Similar data, representing rough first estimates of high altitude convective cloud distributions, are available for 31 radar stations in the United States.

In a study of the frequency of clouds and icing at high altitude, 15,000 weather observations taken at altitudes above 20,000 feet (6 km) were analyzed. These flight weather observations, taken by the Air Force at regular intervals during routine operations, were made primarily over the United States. They were unevenly distributed with the heaviest concentrations over the Great Plains and along the Pacific Coast. Table 5-12, based on the results of this study, gives the frequency with which clouds were encountered at altitudes from 20,000 to 45,000 feet (6 to 13.5 km).

In 1962, pilots in U-2 aircraft over Texas and Oklahoma reported flying around and above cloud tops as high as 65,000 feet (20 km), and in 1963 and 1964 they reported cloud tops at 62,000 to 64,000 feet (19 to 19.5 km). These observations were made in support of the National Severe Storms Project and were oriented specifically toward studying the most severe thunderstorms.

Table 5-13 gives the seasonal frequency of occurrence of cirrus formations over southern England as determined from high-altitude aircraft observations during 1949 to 1952. The frequency of occurrence is relatively high. In the study providing the data in Table 5-13, a relationship was found between the air flow at the 300-mb level and the frequency of cirrus cloud occurrence over southern England. Cirrus occurred frequently when the air at 300-mb level had traversed large areas of the Atlantic Ocean, but seldom occurred in air of continental or polar origin. This would account for the relatively large percentages over southern England where the prevailing wind is usually off the Atlantic.

#### 5.3.4 Horizontal Extent of Cirrus and Convective Clouds

Cirrus cloud formation in middle latitudes can extend over an area up to 1500 miles (2400 km) in length parallel to frontal systems, and 500 miles (800 km) in width. Also, the probable extent of cirrus clouds over the United States during the winter months can be estimated from Figure 5-17. If a flight from Los Angeles to Washington, D.C., a distance of approximately 2500 miles (4000 km) had been made at 20,000 feet (6 km) during the period represented by Figure 5-17, cirrus clouds could have been observed in some amount over practically the entire route.

From observations made by Comet aircraft of high-level clouds in the tropics, the presence of extensive sheets of cirrus clouds appears to be the rule rather

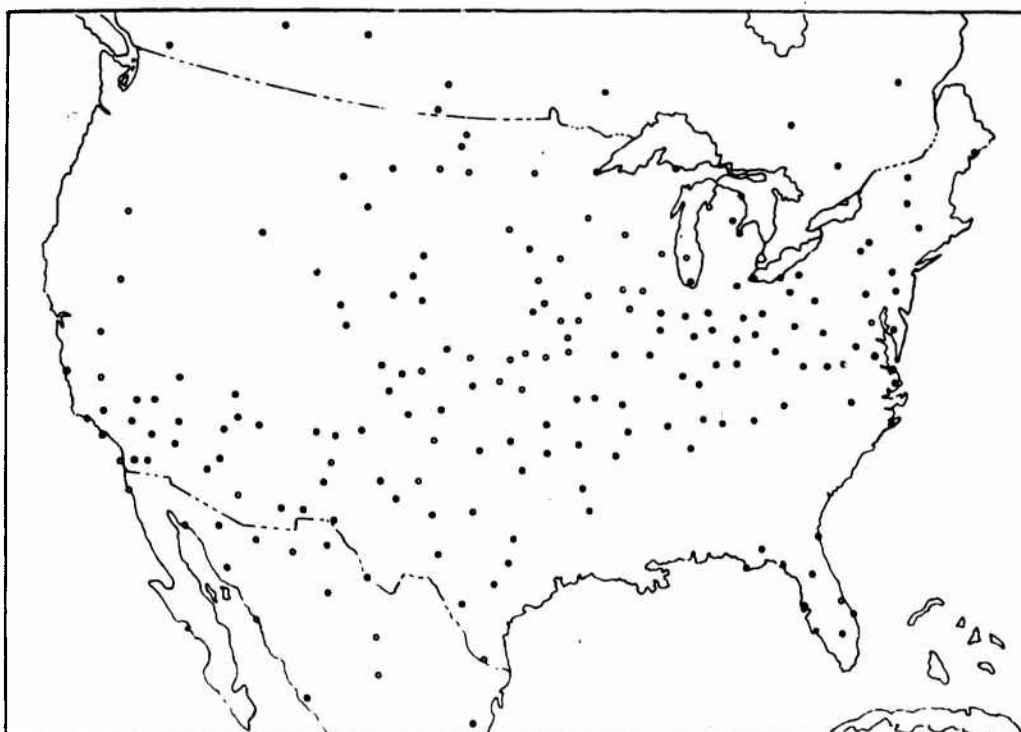
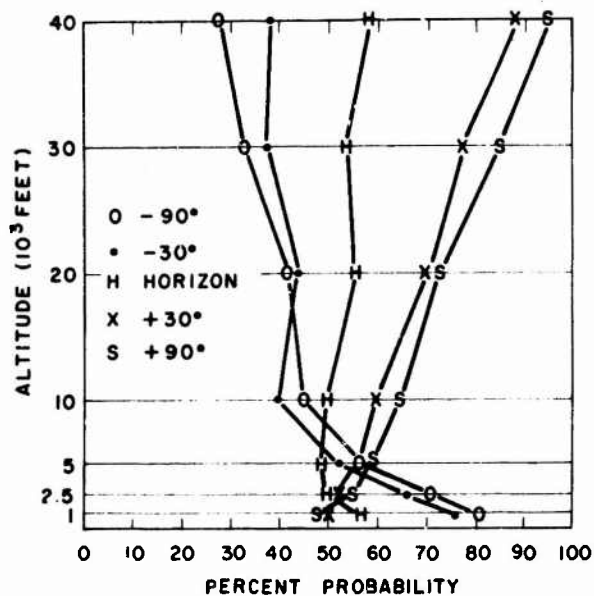


Figure 5-17. Analyses for 1500, 7 December 1948, Reports of Cirrus and of Clear Skies Indicated by Solid and Open Circles, Respectively. (From R. D. Fletcher and D. Sartos, Air Weather Service Tech. Rept. No. 105-81, 1951.)

Table 5-13. Seasonal Frequency of Occurrence of Cirrus Over Southern England. (From R.J. Murgatroyd and P. Goldsmith, Professional Notes, v. 7, no. 119, British Air Ministry)

Season	Percentage of Occasions			
	Cirrus (%)	Distant Cirrus (%)	No Cirrus (%)	No. of Observations
Winter	58	10	32	41
Spring	31	27	42	68
Summer	50	33	17	70
Autumn	47	31	22	64

Figure 5-18. Probability of Clear Lines-of-Sight Over the Northern Hemisphere. (From E. A. Bertoni "Clear Lines-of-Sight from Aircraft," Air Force Surveys in Geophysics No. 196 (AFCRL-67-0435), Air Force Cambridge Research Laboratories, 1967)



than the exception (Durst, 1952). On the African route between Khartoum and Livingston, approximately  $15^{\circ}\text{N}$  to  $15^{\circ}\text{S}$  latitude, continuous sheets of cirrus or cirrostratus clouds were frequently observed with bases between 45,000 and 50,000 feet (13.5 and 15 km). These layers frequently extended over 1600 miles (2600 km) of the route.

Size and shape of high altitude convective clouds have been estimated from radar photographs (Long, et al, 1965). For thunderstorms that have penetrated the tropopause in the midwestern United States, the shape of the cloud is a cone with a diameter-to-height ratio of roughly five to one for the portion of the cloud above the tropopause. However, much of the cirrus blowoff (shield) that is observed from the ground remains below the tropopause. Mean diameter of high altitude convective cells, including the associated anvil, has been estimated at 20 to 30 miles (32 to 50 km).

In Figure 5-18 tentative probabilities of clear lines-of-sight from aircraft are shown for different angles above and below the horizon; the probabilities given are the initial results of a program for estimating cloud effects on lines-of-sight at various altitudes. These curves are hemispheric averages for all months and are not representative of any given season or location; they are based on about 72,000 observations by aircraft crews. Since the observations were taken over a short period of time (about 15 months) and over only a fraction of the hemisphere, the probabilities shown are simply first estimates. These provisional values will be revised as additional observations, currently being taken, are added to the data sample.

### 5.3.5 Maximum Water Content of Clouds

Water in clouds is found in gaseous (vapor), liquid, and solid (ice crystals) states. Water vapor exists at all temperatures and is always present in the atmosphere, even in clear air. Liquid water is found in clouds from about  $25^{\circ}\text{C}$  down to a  $-35^{\circ}$  or  $-40^{\circ}\text{C}$ . Ice crystals are found at all sub-zero temperatures and frequently at a few degrees above zero but generally will not form naturally in the free atmosphere at temperatures warmer than  $-12^{\circ}\text{C}$ .

Water vapor in the atmosphere is indicated by the humidity. For practical purposes, the relative humidity in clouds is 100%. The amount of water vapor depends on the cloud temperature, doubling to tripling for each  $10^{\circ}\text{C}$  increase in temperature. For example, clouds at  $25^{\circ}\text{C}$  will have  $23\text{ g m}^{-3}$  of water vapor whereas those at  $0^{\circ}\text{C}$  will have only  $5\text{ g m}^{-3}$  of vapor.

Because measurements of the amount of water in the liquid and solid states in clouds are not extensive, it is impossible to provide a frequency distribution of the amounts contained in various types of clouds. Information given here is

limited to estimates of the maximum amounts of water (gaseous, liquid, and solid) likely to be encountered in cloud form. Section 5.2.1 gives data on the precipitable and cloud-particle water content of clouds during various surface rates of wide-spread precipitation.

Because the amount of water vapor approximately doubles for each  $10^{\circ}\text{C}$  rise in temperature, more water will be available during the summer, and heavier clouds are to be expected below 35,000 feet (10.5 km). Investigations of warm convective clouds (types found to have the highest water content) indicate an average liquid water content 4 to 5 times that observed in the winter, and 5 to 10 times that observed in stratus clouds irrespective of season (aufm Kampe and Weickmann, 1957). Data from these investigations are shown in Table 5-14 and Figures 5-19 and 5-20. The droplet size, water content, visibility, and droplet concentration data in Figure 5-20 represent average values regardless of the altitude at which they were collected, whereas Figure 5-19 depicts these parameters as functions of height above the base in convective type clouds.

The water content curve in Figure 5-19 indicates that cumulonimbus clouds contain the greatest amount of liquid water. The maximum content observed,  $10 \text{ g m}^{-3}$ , was found in a cumulonimbus cloud near 13,000 feet (4 km) above the cloud base. The cumulonimbus data have been questioned, however, because there was evidence that a number of raindrops was included in each cloud sample. Figure 5-19 also indicates that the liquid water content of cumulus congestus clouds, from which there is apparently no precipitation, can exceed  $6 \text{ g m}^{-3}$ . The formation of precipitation inside a cumulus cloud is a complex function of physical, chemical, and meteorological variables that are poorly understood. Therefore, when precipitation is not actually falling from a cloud, it is difficult to determine

Table 5-14. Observed Liquid Water Content of Cumulus Type Clouds Over New Jersey and Florida During the Summer

Clouds		Water Content ( $\text{g m}^{-3}$ )	
Type	Temp ( $^{\circ}\text{C}$ )	Average	Maximum
Cumulus Humilis	10 to 24	1.0	3.0
Cumulus Congestus	3 to 11	2.0*	6.6
Cumulonimbus	10 to -8	2.5	10.0

\* estimated

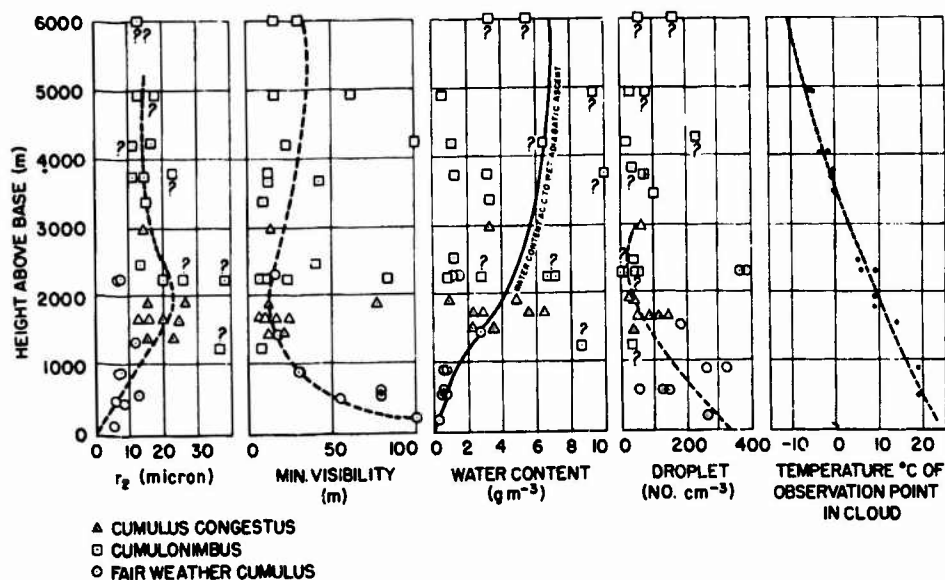


Figure 5-19. Physical Properties in Cumuliform Clouds Versus Heights Above Base of Cloud

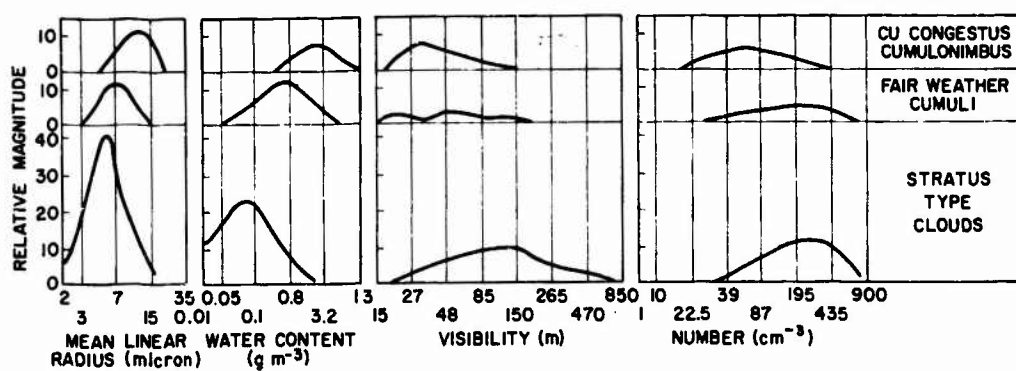


Figure 5-20. Physical Properties of Different Types of Clouds (From aufm Kampe and Weickmann, 1957)

what part of the total liquid water content should be classified as cloud particles and what part as suspended precipitable water. Apparently the maximum liquid water content that can exist in a nonprecipitating cloud is between 6 and 10  $\text{g m}^{-3}$ . A study by the University of Chicago indicates cloud water densities of at least 1.7  $\text{g m}^{-3}$  are required before rain is produced.

From Table 5-14, the water content appears to be increasing with decreasing temperature. This can be attributed to the higher flight altitudes at which observations were made in the more developed convective clouds. Theoretically, more moisture is available for condensation at the lower level because of higher temperatures and, therefore, a heavier cloud density would be expected. Strong vertical currents in convective clouds of this type, however, are such that condensed cloud particles originating in the lower levels will be carried aloft. In well-developed convective clouds, with no precipitation, the maximum liquid water content occurs near the top. As the cloud builds to high altitudes and the drop size goes up, down drafts occur. Thus, the maximum liquid concentration will be observed at an altitude corresponding to 1/2 to 7/8 of the cloud height. After precipitation begins there will be little variation in the amount of liquid (or frozen) water with height, from the base of the cloud to the level of maximum concentration, because falling raindrops and downward currents redistribute the liquid.

A temperature of about 20°C appears reasonable for a region near the lower part of cumulonimbus clouds (not indicated in Table 5-14 because observations were made only at the higher levels), yielding a water vapor content of 17  $\text{g m}^{-3}$ . A rough estimate of the maximum water content in cloud form of a cumulonimbus cloud at this level, using the 8  $\text{g m}^{-3}$  of liquid water, a mean value between the maximum amounts observed in precipitating and nonprecipitating clouds in Figure 5-19, and the above vapor content, would be 25  $\text{g m}^{-3}$ . This value probably would include some precipitable water held in suspension and would be encountered near the base of cumulonimbus clouds, about 2000 feet (600 m) above the ground. The liquid water content would remain fairly constant to altitudes of 15,000 to 20,000 feet (4.5 to 6 km) but the vapor will decrease rapidly with height commensurate with decreasing temperature. If total available moisture is considered, this value could be considerably higher. For example, calculations based upon extreme tropical rains indicate a liquid water content of 30  $\text{g m}^{-3}$ , mostly as raindrops. This value added to the 17  $\text{g m}^{-3}$  of water vapor would give a maximum value of 47  $\text{g m}^{-3}$ .

Few direct observations have been made of the water content of clouds above 25,000 feet (7.5 km). The estimates of the maximum amount of moisture likely to be encountered in clouds above 25,000 feet (7.5 km) are based on the few

observations available, theoretical studies, and extrapolation upward from lower levels; the information is semiquantitative. It may be used, however, as a first approximation in determining, for example, the effect of the water content in clouds above 25,000 feet (7.5 km) on a particular jet engine or aircraft design.

Usually, cloud formation above 25,000 feet (7.5 km) will be composed entirely of ice crystals and this total solid water content will not exceed  $0.1 \text{ gm}^{-3}$ . Temperature within the clouds will range from  $-20^{\circ}$  to  $-52^{\circ}\text{C}$ , depending on altitude. Excluding cumulonimbus clouds, which frequently extend above 25,000 feet (7.5 km), the water content when both liquid and ice are present in clouds at or above 25,000 feet (7.5 km) will be between 0.1 and  $1.0 \text{ gm}^{-3}$ . Temperatures at 25,000 feet (7.5 km) when this extreme water content is experienced will be near  $-20^{\circ}\text{C}$ . Temperature and water content will decrease with increasing altitude.

In cumulonimbus clouds the water content (liquid and ice) may occasionally attain a density of  $15 \text{ gm}^{-3}$  at 25,000 feet (7.5 km) (Roys and Kessler, 1966). This value will decrease rapidly at altitudes above 35,000 to 40,000 feet (10.5 to 12 km). Temperatures in the clouds above 25,000 feet (7.5 km) will range from  $-15^{\circ}$  to  $-50^{\circ}\text{C}$ , depending on altitude and latitude.

#### 5.1 NOCTILUCENT CLOUDS, by R.A. Skrivaneck

Noctilucent clouds are normally observed during the summer months in northern and southern latitudes which roughly correspond to the auroral zones. The uniqueness of these clouds is the high altitude at which they occur, about 80 km. Tinged a silvery blue, they usually form billows and waves which resemble high thin cirrus clouds and can easily be mistaken for such. The clouds are so optically thin that bright stars shine through them. Figure 5-21 is a photograph of a noctilucent cloud.

Noctilucent clouds almost always appear in the same well-defined region of the sky ( $10^{\circ}$  to  $20^{\circ}$  above the horizon) between the twilight arch at the horizon and the night sky overhead. From the horizon to about  $10^{\circ}$  above, sunlight scattered by the lower atmosphere outshines the clouds. As Figure 5-22 shows, the optimum illumination and contrast exist when the sun is between  $6^{\circ}$  and  $12^{\circ}$  below the horizon so that a large part of the sky behind and partly above the observer is in the shadow of the earth. The visible clouds may be part of a system covering much larger regions of the sky. Although occasional bright displays have been seen even up to the zenith in northern Scandinavia, the clouds overhead at one place are usually visible only to observers elsewhere who can see them at a lower



Figure 5-21. Photograph of Noctilucent Cloud

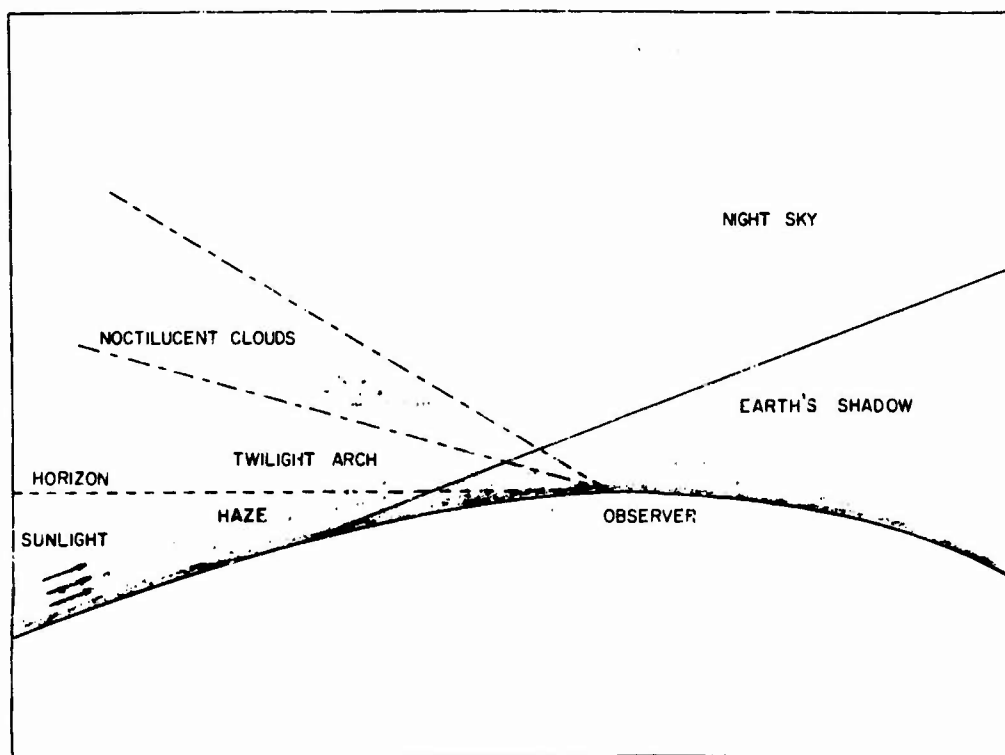


Figure 5-22. Diagram of Twilight Conditions Associated with Noctilucent Clouds

angle. Binoculars or a telescope exclude the light of the twilight arch from the eyes and increase the apparent contrast in the wave structure of the clouds. From the record of observations, it seems that the clouds are visible mostly between the latitudes of  $45^{\circ}$  and  $80^{\circ}$ .

Noctilucent clouds have been observed over an altitude range from 74 to 92 km; the average altitude is 82 km. Horizontal motion of the clouds, which is attributed to winds, can be as high as several hundred meters per second. The gross cloud drift is predominantly from the northeast to the southwest. The waves in the clouds are thought to be gravity waves (Witt, 1962); wavelengths range from 5 to 50 km and amplitudes from 0.5 to 4 km. The wave crests do not partake of the mass motion of the clouds. Often they appear stationary with respect to the ground and sometimes seem to travel in the direction opposite to the mass motion; this phase velocity appears to be a function of the wavelength.

The clouds scatter sunlight in accordance with Mie theory (aerosol scattering, Sec. 7.1); the scattered light is elliptically polarized. The degree of polarization ranges from about 5% at a  $20^{\circ}$  scattering angle to about 50% at a  $60^{\circ}$  scattering angle.

Based upon the results of particle collection experiments performed in 1962, it was postulated that noctilucent clouds were composed of particles of which the nuclei at least were extraterrestrial in origin. Furthermore, it was believed that many of the nuclei were surrounded by an ice coating, which could increase the particle diameter by as much as ten times. The particle concentration in a vertical column through a cloud sampled during a moderate display was greater than  $10^7 \text{ cm}^{-2}$ . This is at least  $10^3$  greater than the particle concentration when no clouds were visible. Due to the very small size of the particles, chemical data has been extremely difficult to obtain. X-ray analysis gave marginal indications for the presence of iron, nickel, and silicon, while sulfur was definitely identified. Unfortunately, it was not possible to determine whether the sulfur signal originated from the nucleus, the coating on the nucleus or both (Skrivanek, 1966). The nuclei have a size distribution of the form

$$\frac{dN}{dr} \propto r^{-p}, \quad (5-8)$$

with a sharp cut off at the lower size limit  $r = 0.02\mu$ ;  $r$  is particle radius, and  $4 < p < 5$ .

The clouds are probably not more than several kilometers thick (Hemenway et al, 1964). Since 1962, several other attempts were made to collect particle samples from noctilucent clouds. None of the attempts have been successful in duplicating the results of the 1962 experiments; consequently some doubt exists at present concerning the true nature of noctilucent clouds.

Several hypotheses have been advanced to explain the sources and mechanisms contributing to the occurrence of the clouds; however, in general, they are still unproven. One postulates a meteoroid origin, suggesting the occurrence of clouds to be coupled to periods of increased meteoroid influx (meteor showers). Another suggests that terrestrial material is raised from a lower altitude by vertical updrafts. Still another suggests that the particles are meteoritic in origin, but their increased concentration in a thin layer is caused by the occurrence of slight vertical updrafts, rather than by increased meteoroid influxes. The most unusual explanation is that of Witt (1969), who suggests that the clouds are composed of molecular agglomerates consisting of a central ion surrounded by molecules of water.

Witt and Martin-Lof made temperature and wind measurements in the presence and absence of noctilucent clouds that indicate a strong correlation between the clouds and the meteorological conditions in the mesopause. When clouds were observed, a temperature minimum of 130 K at 84 km was measured; the winds were relatively quiet. During the no-cloud condition, a temperature minimum of 150 K was observed at 81 km and strong winds with shears of  $30 \text{ m s}^{-1} \text{ km}^{-1}$  were measured in the same altitude region. The use of a ground-based laser radar has recently provided an additional tool for the study of noctilucent clouds. Thus far, most of the published data resulting from this technique has been marginal due to the very small signals received by the detectors. However, because this technique offers such a potential wealth of information, it is likely that it will receive a great deal of attention in the next few years.

Within the past few years, noctilucent clouds have received an increasing amount of attention. The quantity and quality of the observations have greatly improved. The number of observing stations has been increased, including establishment of sites in the southern hemisphere. Noctilucent clouds have also been sighted in the southern hemisphere (Fogel, 1965). A Noctilucent Cloud Data Center has been established for the purpose of collecting and disseminating observational information. An observation manual has been prepared under the auspices of the World Meteorological Organization and will receive world-wide distribution.

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13. ABSTRACT The need for geophysical and astrophysical information is critical for the design of aircraft, missiles, and satellites. The HANDBOOK OF GEOPHYSICS AND SPACE ENVIRONMENTS is an attempt by the U.S. Air Force to organize some of these data into compact form. The water content of the atmosphere is discussed in this chapter. Data are provided on the frequency of occurrence of various surface rates of rainfall, hail, the vertical distribution of precipitation intensity, and the particle size distribution in widespread precipitation. Information on the types and limitations of cloud data and of the distribution and water content of clouds is included.		

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